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DOI: https://doi.org/10.1063/1.3458545

Originally published at:
Moore, B (2009). The dark and light side of galaxy formation: is an end in sight? In: Hunting for the Dark: the Hidden Side of Galaxy Formation, Qawra, Malta, 19 October 2009 - 23 October 2009. American Institute of Physics, 3-12.
DOI: https://doi.org/10.1063/1.3458545

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Citation: AIP Conference Proceedings **1240**, 3 (2010); doi: 10.1063/1.3458545
View online: http://dx.doi.org/10.1063/1.3458545
View Table of Contents:
http://scitation.aip.org/content/aip/proceeding/aipcp/1240?ver=pdfcov
Published by the AIP Publishing

The Dark and Light Side of Galaxy Formation: Is an End in Sight?

Ben Moore

Institute for Theoretical Physics, University of Zurich, Switzerland

Abstract. I will briefly review our understanding of disk galaxy formation, highlighting what we think we know and what we would like to know. Our knowledge of galaxy formation is driven by observations. Numerical simulations are a powerful tool to study these problems, but they are still unable to answer some of the most simple questions about how galaxies form and evolve. However, they are rapidly becoming more sophisticated and accurate - for example we can now resolve molecular cloud formation within disk galaxies that form within a hierarchical cosmological context. Optimistically, we are within reach of achieving a reasonable understanding of the origin of the Hubble sequence within the next decade.

INTRODUCTION

The fuzzy band of light in the night sky was speculated to be distant stars by Democratis around 400BC, but it was not until the invention of the telescope in 1608 by Hans Lippershey that this was finally verified by Galileo in 1610 who first resolved the Milky Way into millions of stars. Since Hubble determined that the fuzzy nebulae were distant galaxies, astronomers have attempted to carefully visually classify and catalogue galaxies into common sequences. Most famous of these, the Hubble sequence, describes galaxies according to the complexity of their appearance - a sequence that is often mistakenly interpreted as an evolutionary sequence since the scheme smoothly stretches from bulgeless disks, through S0's to ellipticals. The subject of this contribution is to give a modest overview of our current understanding of how galaxies form and evolve from a theoretical perspective, and to discuss open questions that will be addressed in future work.

Visual inspection of telescope images reveals a huge diversity in the morphological appearance of galaxies. Furthermore, the appearance of an individual system is very different in different wavelengths. In order to reproduce the wide variety of galaxy morphologies, many transformation mechanisms have been invoked. These typically invoke gravitational and hydro-dynamical interactions, which can move galaxies across the Hubble sequence and create the diversity observed in our Universe. To date, these processes have generally been studied using numerical simulations of pre-constructed idealized galaxy models. The ultimate goal is to develop our computational techniques such that environmental effects and morphological evolution can be followed within the cosmological model of a hierarchical universe.

It has been almost 30 years since the theoretical cosmological framework for the evolution of structure within a cold dark matter (CDM) dominated universe was pioneered [1]. More recently, dedicated campaigns of space and ground based observations have

CP1240, *Hunting for the Dark: The Hidden Side of Galaxy Formation*
edited by V. P. Debattista and C. C. Popescu

precisely measured the initial conditions from which structure forms in our Universe - tiny perturbations imprinted on the mass distribution like a network of ocean ripples [e.g. 2]. The past decade in particular has proven to be an exciting time in cosmology. Astronomers have measured the fundamental parameters that govern the evolution of the Universe. The matter and energy densities, the expansion rate and primordial power spectrum are now well constrained; however, only about one percent of the Universe has been physically identified and understood. Thus although the initial conditions for structure formation are known, it is not known what the dominant components of matter and energy actually are. How these fluctuations in the dark matter and baryonic components form galaxies, stars and planets, involves complicated non-linear processes including gravity, hydrodynamics, radiation and magnetic fields. Linear theory calculations only take us so far and we must rely on numerical simulations to follow the detailed structure formation process.

Until recently it was difficult to stringently test the predictions of a given cosmological model. Simulations are the ideal means by which to relate theoretical models with observational data and advances in algorithms and supercomputer technology has provided the platform for increasingly realistic astrophysical modelling. For example, simulations simply could not resolve the central regions of dark matter halos where kinematic and lensing observations constrain the mass distribution [3, 4]. There has been steady and significant progress in this area - reliable and fundamental predictions of the clustering properties of the dark matter have been made via massively parallel computations [5, 6, 7]. The "cusp" and "satellite" problems for the standard cold dark matter represent real observational tests of the properties of a new fundamental particle that makes up most of the mass of the Universe - this is a testament to the achievements of modern numerical simulations. This ability to predict the non-linear behaviour of dark matter clustering has stimulated much work in the observational astronomy and astroparticle physics communities.

Our theoretical understanding of galaxy formation is some way behind the stream of quality observational data that comes from ground and space based facilities around the world. Whilst theorists are still trying to understand how galaxies assemble themselves from the dark matter and baryons in the Universe, observational astronomers have exquisite data in multi-wavelengths with high resolution spectral information, element abundances, colour maps and kinematical data. Theorists have not yet succeeded in making a single realistic disk-dominated galaxy via direct simulation - it is still an open question as to how the baryons collect at the centres of galaxies and what causes and regulates star and star-cluster formation.

Some observational facts about galaxies:

• All galaxies are observed to sit at the center of an extended distribution of dark matter

• Galaxies range in baryonic mass from $10^3 M_\odot$ to almost $10^{13} M_\odot$ (from the smallest satellites of the Milky Way to the giant cD galaxies in clusters)

• No one has observed a dark galaxy (a halo with no baryons) even though cold dark matter halos are predicted to span a mass range from about $10^{-6} M_\odot$ to $10^{15} M_\odot$

• No galaxy has been found to contain gas but no stars

• The tight Fisher-Tully and Faber-Jackson relations, relating luminosity to mass, imply that galaxies form in an well behaved and non-stochastic way

• Star formation is physically complex, but follows well defined global scaling laws

• The baryon fraction of halos decreases from cluster scales, which have the universal baryon fraction, to dwarf galaxies which have only $\approx 1\%$ of the universal fraction

• Most of the stars in the Universe are inside ellipticals, but most galaxies are dSph's and disky systems

• The morphologies of galaxies varies with environment and redshift

• The luminosity function of galaxies below L_* scale as $n(L) \approx L^{-1}$, whereas the mass function of dark matter halos is steep $n(M) \approx M^{-2}$

• There are always examples of galaxies that are exceptions from the rule.

PROGRESS AND OPEN QUESTIONS

Our Milky Way and its local environment, is a "Rosetta Stone" for understanding galaxy formation and evolution and for testing cosmological models. It contains several distinct old stellar components that provide a fossil record of its formation - the old stellar halo, globular clusters and satellite galaxies. We can begin to understand their spatial distribution and kinematics in a hierarchical formation scenario by associating the proto-galactic fragments envisaged by Searle and Zinn thirty years ago, with the rare peaks able to cool gas that are predicted to form in the cold dark matter density field collapsing at redshifts z>10.

Hierarchical structure formation simulations can be used to explore the kinematics and spatial distribution of these early star-forming structures in galaxy halos today [8, 9]. Most of the proto-galaxies rapidly merge together, their stellar contents and dark matter becoming smoothly distributed and forming the inner Galactic stellar and dark halo. The metal-poor globular clusters and old halo stars become tracers of this early evolutionary phase, centrally biased and naturally reproducing the observed steep fall off with radius. The most outlying peaks fall in late and survive to the present day as satellite galaxies. The observed radial velocity dispersion profile and the local radial velocity anisotropy of Milky Way halo stars are successfully reproduced in this toy model. If this epoch of structure formation coincides with a suppression of further cooling into lower sigma peaks then the rarity, kinematics and spatial distribution of satellite galaxies can be produced. Recent numerical work has indicated that the Local Group may have been re-ionised from outside, from the nearby forming Virgo cluster of galaxies which collapsed before our own Milky Way [10]. This leaves observable effects on the distribution of the old stellar components. However, the above qualitative scenario needs be tested rigorously using simulations that follow all of the physical processes, not just the dark matter component as all previous studies have used [11, 12].

Although the theory behind galaxy formation appears well defined, many of these individual assumptions remain untested and no group has been able to successfully simulate the formation of a Milky Way like disk galaxy that resembles observed Sb-Sc galaxies. Very recently, there has been a paradigm shift in our understanding of how galaxies obtain there baryons - rather than cooling flows from a hot ionised gaseous halo component, cold inflowing streams of baryons can dominate the accretion [13, 14, 15]. Various groups are coming close to resolving galaxies using computational techniques [e.g. 16], however these simulations resulted in bulge/spheroid dominated systems with disks that are too small. It is not known if this is a deficiency in the model or a problem with the numerical simulations [17]. Forming realistic disk galaxies is widely recognised as a major challenge for both numerical simulations and for the CDM hierarchical structure formation model. The ultimate goal is to calculate the formation of the Milky Way and the Local Group of galaxies within our concordance cosmological model, in exquisite detail so as to make theoretical predictions for forthcoming ground and space based missions such as Vista or Gaia.

Some things we don't know about galaxy formation:

• How do galaxies acquire their baryons?

• Is the halo mass the main quantity that determines the morphology of a galaxy?

• How do disk galaxies form, in particular bulgeless Sc/Sd galaxies?

• How do elliptical galaxies and S0 galaxies form?

• The merger history of halos is extremely varied, how do tight scaling laws result?

• What prevents all the low mass substructures and halos forming stars?

• How does SN feedback in small haloes and AGN feedback in massive haloes affect galaxy formation?

• What mass dependent processes regulate star-formation such that the observed luminosity function of galaxies can be reconciled with the mass spectrum of CDM haloes?

Modelling issues

I. The ISM

Modelling the thermodynamics of the interstellar medium (ISM) is an important aspect of galaxy formation and evolution. The ISM has at least three main phases that are in approximate pressure equilibrium; a hot ($\approx 10^6$K) low density (0.01-0.00001 atoms/cm^3) ionised space filling plasma that fills the holes and bubbles within the disk ISM and extends to tens (and possibly hundreds) of kpc into the Galactic halo [18, 19], a warm (100-1000K) diffuse phase with densities up to one atom/cm^3 [19] and the dense (>100 atoms/cm^3) cold molecular H2 dominant phase with temperature < 50K [20]. The phases are constantly mixed by supernovae explosions that inject large quantities of thermal energy and momentum in the ISM. The different phases in the ISM coexist as the result of thermal balance between radiative heating and cooling at different densities and, at the same time, thermal instability (perhaps coupled with gravitational instability) that determines the emergence of the dense molecular phase in which star formation takes place. Furthermore, the formation of a galaxy should not be considered within a closed box. There are constant accretion events of satellites and new gas, cooling flows and recycled material from stripped debris as well as galactic fountains.

Molecular gas is formed and destroyed via a number of microscopic interactions involving ions, atoms and catalysis on dust grains. These processes become biased towards the formation rather than towards the destruction of molecular hydrogen only at densities > 10 atoms/cm^3. A great deal of energy in the interstellar medium is non-thermal; this turbulent energy, which is essentially observed as random gas motions, is supersonic and several times larger than the thermal energy at the scale of giant molecular cloud complexes. Turbulent kinetic energy is thought to be the main agent that supports the largest molecular clouds (> $10^5 M_\odot$) against global collapse. The partial suppression of gravitational collapse owing to turbulent support also explains the low efficiency of star formation in our Galaxy (only a few percent of the molecular gas mass present in the Milky Way appears to be involved in forming stars). Modelling the ISM is non-trivial. Recently, [21] questioned the ability of smoothed particle hydrodynamical codes (SPH) to follow multiphase gas and basic flow instabilities such as Kelvin-Helmholz. Galaxies form from a turnaround region that is a megaparsec in size (the angular momentum is generated from a region larger than 10Mpc). On these scales the gas density is 10^{-7} atoms/cm^3, and we need to follow this region as the gas collapses to parsec scale molecular clouds with densities larger than 100 atoms/cm^3. Simultaneously resolving the star-formation process itself, inside molecular cloud cores within a cosmological context is a decade away. However, a dynamic range of 5 decades in length and 7 in density necessary to resolve GMC formation has recently been achieved in the highest resolution adaptive mesh refinement (AMR) simulations [22].

II. Subgrid treatments of star-formation and feedback

Even in these simulations and for the foreseeable future, modelling the physical processes of star-formation, supernovae feedback and radiative processes from stars relies on "sub-grid" algorithms. These processes can not be simulated directly due to resolution issues and are implemented by hand as realistically as possible, relying on observational scaling laws and theoretical modelling.

Even the thermodynamics of the ISM is partially sub-grid, since current simulations typically lack resolution below a hundred parsecs which sets a maximum density that can be resolved of the order one atom/cm^3, which is close to the density of the warm neutral medium. For this reason cooling processes that are important below T$\approx 10^4$ K are usually neglected. Likewise, radiative heating is partially determined by the thermal and turbulent energy injection from supernovae explosions, accreting massive black holes and also the radiation background produced by stars, or by cosmic-ray and x-ray heating. These processes are simply included as a constant heating term in the internal energy equation.

Star-formation in these simulations is treated in an embarrassingly simplistic way - once the gas reaches some threshold, "star particles" (which individually represent star-clusters) are created. This density is taken to be $\approx 0.1 - 1$ atom/cm^3, since this is the highest density that can be followed at the current resolution. In essence, the Schmidt-Kennicutt law (the correlation between gas density and star-formation rate) is implemented by hand into the simulations.

Once these super star sized particles are created, an initial mass function is assumed which can be evolved to determine what fraction of the 'stars' explode as supernovae, returning energy and heavy elements to the ISM. How this energy return is treated ranges from dumping thermal or kinetic energy into the surrounding gas, to halting the radiative cooling of gas for a timescale of about 20 million years. This latter approach attempts to account for energy dissipation timescale of the unresolved turbulence generated by the supernovae.

III. Making disk galaxies

The angular momentum problem has received a lot of attention in the literature - namely the fact that disks that form within cosmological simulations do not lie on the Tully-Fisher relation (they are rotating too fast for the amount of stars they have formed. However as resolution increases and sub-grid modelling has improved, galaxies are produced which lie quite close to the relation. One of the most puzzling remaining problems is that until recently, no simulation has managed to produce a pure disk galaxy - all simulated galaxies have a significant bulge/spheroid component which arises in different ways: (i) massive gas clumps form dense star clusters which rapidly sink to the centers of halos, (ii) too many satellites accrete and merge with the forming galaxy and (iii) gas at the centers of halos continues to form too many stars.

Recently [23] simulated the formation of a small dwarf spiral galaxy that had a negligible bulge component. These SPH simulations have a high spatial resolution due to the small mass of the system. By invoking strong supernovae feedback, star formation was inhibited and the system was violently stirred by the motions of stellar and gaseous clumps. However, it is not clear that supernovae feedback is the key to understanding the formation of larger disk galaxies like the Milky Way. It may be the case that star-formation efficiency plays the most important role, moreover, this may be a time dependent process closely linked to H2 formation [24].

Another origin of all of these problems is possibly due to the fact that radiative processes are not accurately included. Star clusters that form would quickly evaporate the surrounding gas leaving the stellar component unbound which would disperse before it sinks to the halo center. The proto-galaxies that form at high redshift in the simulations have far too many baryons and are so dense that they can sink intact into the central galaxy creating a spheroid. Those proto-galaxies that accrete late form a population of satellites that are too luminous and too numerous. Reducing the baryon fractions in these systems as they form, perhaps by reionisation and photoionisation would greatly reduce the numbers of stars they could bring into the central galaxy, and also make them easier to disrupt in the outer halo. Finally, the central cold neutral hydrogen component at the halo center that continues to form stars is rarely observed in galaxies - radiation from OB stars from the bulge or inner disk would be sufficient to keep this material ionised or to prolong the cooling timescale such that star-formation in the bulge region would be greatly reduced.

Our current understanding

The first goal that is achievable in the near future is to resolve the formation of molecular clouds within the gaseous disks that form at the centers of the dark matter halos. This alone would allow many realistic comparisons to existing data and allow us to study how galaxies evolve in different environments. Following this evolution to a redshift zero with parsec scale resolution is likely to be achieved within the next 5-10 years. (Resolving the fragmentation and collapse of individual clouds, is perhaps several decades away given existing algorithmic and computational limitations.) Simulations that spatially resolve molecular cloud formation within a cosmological context would allow us to make enormous progress in understanding galaxy formation and the origin of the Hubble Sequence.

How galaxies get their baryons

There are two key phases to galaxy formation -first, the early rapid virialisation and assembly of the dark matter and old stellar components, a stage when the surviving satellite distribution is established, and second, the longer term quiescent stage when secular disk growth proceeds. The complexity in these processes can only be followed with numerical simulations. Semi-analytic calculations attempt to incorporate these results to make predictions for the global properties of galaxies for large scale surveys. The classic picture of galaxy formation within the cold dark matter (CDM) scenario assumes that the accreted gas is shock heated to the virial temperature (i.e. a temperature in which the kinetic energy of the gas balances the gravitational potential energy of the mass distribution) cools radiatively and rains down to form an inner star-forming rotating disk. Recent theoretical studies [25, 13] have demonstrated that accretion of fresh gas via cold infall can in fact be the dominant process for gas accretion for halo masses below $10^{11} M_{\odot}$. In these halos, the cooling time for gas of temperature T$\approx 10^4$K is shorter than the timescale of gas compression and shocks are unable to develop. Cold accretion persists in halos above this mass at z=2 whilst the classical hot mode of gas accretion dominates at lower redshifts. Because of insufficient spatial resolution, these studies could not follow the evolution of the accreting gas and how the cold streams connect to the central galaxies.

Figure 1 of [22] captures the complex disk formation process where we observe gas reaching the disk via three very distinct ways. This striking image ties together many aspects present in modern theories of galaxy formation and highlights new complexities. Cold streams of gas originating in narrow dark matter filaments, effectively penetrate the halo and transport cold metal-poor gas right down to the proto-galactic disk to fuel the star forming region. A comparable amount of metal enriched material reaches the disk in a process that has previously been unresolved - material that is hydrodynamically stripped from accreting satellites, themselves small disky systems, through the interaction with the hot halo and frequent crossings of the cold streams. The cold gas streams into the halo on a highly radial trajectory, eventually forming more orderly rotational motion in an extended disk through two mechanisms. A cold stream can gravitationally swing past the halo center and subsequently collide with a cold stream inflowing from an opposite direction: As the cold stream enters the inner halo it also feels a high confining pressure from the hot halo which has a significant rotational component within about 40kpc. Shocks from these collisional processes are quickly dissipated since the cooling times are very short resulting in a denser configuration for the cold gas. As the infalling stripped material and streams lose their radial energy through these interactions, it connects to the inner disk as extended dense spiraling arms that progressively slow down to match the highly ordered inner disk rotation. The details of the spiral structure and secular instabilities within such cosmological simulations has yet to be explored in detail. Cold, metal-poor, pristine gas flowing down narrow filaments; metal enriched gas, stripped from accreting satellites; and cooling flows from the hot halo are all significant sources of baryons. This simulation is amongst the first of its kind to achieve a resolution that can resolve giant molecular cloud formation within a cosmological context (50 parsec resolution in the AMR grid and over 10^7 dark matter particles).

Baryon fractions

The baryonic inventory of galaxies of different types and luminosities gives us very important information as to how they form and the processes that affect their formation and evolution. It has been established that large galaxies and galaxy clusters have captured close to the universal baryon fraction available (roughly 6:1 relative to the dark matter component). However, lower mass galaxies have retained today just a small fraction of this value c.f. the "baryonic Tully-Fisher relation" [26, 27]. For example, the Milky Way has captured about 50% of the available baryons [28] whilst nearby M33, the proto-typical late type disk galaxy (close to type Sd) has only $\approx 2\%$ of the universal baryon fraction [29]. Dwarf spheroidals are even more extremely dark matter dominated [30], however additional environmental effects such as tidal stripping and ram-pressure act on these systems as they orbit with the Galactic halo. There are at least two plausible models for the origin of this relationship between baryonic mass and halo mass: Possibly feedback from stars (supernova and the UV background radiation) is more efficient at expelling gas in smaller halos, or perhaps reionisation preheats the gas preventing it from cooling efficiently within less massive halos. For isolated galaxies less massive than the Milky Way, the baryon fraction decreases rapidly, $M_{baryon} \approx V_{vir}^4$, such that the smallest galaxies have captured and cooled just a few percent of the available baryons. Note that if all halos kept hold of the universal value, this relation would scale as $M_{baryon} \approx V_{vir}^3$ (simply resulting from the top-hat collapse model [31]). Reproducing the observed baryon fractions of galaxies is perhaps the most fundamental goal that should be achieved for several reasons. In particular, it may help resolve the discrepancy mentioned above between the mass function of halos and the luminosity function of galaxies. If stars form in proportion to the baryon fraction then we have the fact that the number of stars per halo gives a luminosity $L \approx M_{baryon} \approx V_{vir}^4 \approx (M_{halo})^{4/3}$. Inserting this relation between L and halo mass into the CDM mass function we find a closer agreement between the faint end luminosity function and the halo mass spectrum. Finally, it should be noted that disks that have a lower baryon fraction are considerably more stable against instabilities such as bar formation. Indeed, isolated disk simulations of M33 type galaxies could only be reproduced in models that began with a lower baryon fraction [32]. Thus one can also speculate that in order to create pure disk component galaxies, some mechanism for keeping most of the available baryons at large distances from the halo center is required.

During and after its formation, a galaxy can be transformed between morphological types through a variety of physical processes, thus creating the entire Hubble sequence and the observed diversity in galaxy types. The starting point for most scenarios for morphological evolution is a disk galaxy. However, once a disk has formed, there are a number of mechanisms that can transform its morphology. Merging, gravitational stripping, harassment, starvation, ram-pressure stripping, canabalism... and many other dire sounding processes, all can move a galaxy across the Hubble sequence.

SUMMARY

The origin of galaxies is a hot topic in astrophysics today with lots of existing data and much more on the way. In the next decade, ground and space based observations are aiming to detect structure formation at very high redshifts, even before the epoch of reionisation. Such observations will provide strong constraints on our standard model for structure formation. Unfortunately perhaps, there is no compelling alternative to the LCDM model, therefore for the time being we can adopt the cosmologists 'standard model' which gives us the initial conditions within which to 'create galaxies'. The role of simulations and theoretical work is to see if we can understand structure formation within this model.

Galaxy clusters provide some of the strongest evidence for the fact that we live in a hierarchical Universe. It is remarkable that beginning with linear fluctuations in the matter component, such massive structures arise, each containing many thousands of galaxies. The galaxies must form before the cluster, merging hierarchically to create the final virialised systems - they certainly cannot form after the cluster since the baryons in the cluster are too hot to accrete into galactic halos and galaxies are moving too fast to merger together. This hierarchy is mimicked exactly within dark matter simulations. Cluster mass halos contain many thousands of galactic mass halos, each a remnant of the merging hierarchy. The outer regions of these satellites are stripped away contributing to the smooth mass distribution in the cluster. The central regions survive and their kinematics and spatial distributions match the observations remarkably well.

Galactic halos themselves preserve the merging hierarchy in a self-similar way, each containing thousands of smaller dark matter substructures. There is some evidence for this from the small observed satellite population of galaxies, however the numbers of observed substructures is tiny compared to galaxy clusters. On these scales astrophysical processes can keep many of the substructures dark. However, if they could be detected then this would provide the strongest evidence that we live in a cold dark matter dominated universe. Their non-detection would be the signature that the power spectrum of fluctuations is truncated on small scales, such as might arise from a warm dark matter component.

Theoretical work is slowly catching up to the existing data and it is interesting to ask the question, when will we know if we have a successful theory of galaxy formation? This needs to be more than just a beauty contest. Simulations of galaxy formation in a cosmological context should be able to reproduce the diversity we see in the Universe and the scaling laws that galaxies satisfy as a function of redshift. I believe that such simulations will be carried out within this decade. Accurate numerical simulations are also needed to guide and interpret observational work that attempts to connect astrophysics with fundamental physics. For example, the cross section between neutralinos and baryons may be much smaller than the experimental searches anticipate and detecting dark matter in laboratory experiments may prove futile. In this case, astrophysical observations combined with numerical simulations may be the only way to constrain its nature. Likewise, measuring cosmological parameters to a high precision in order to constrain the properties of the dark energy, requires equally precise predictions for how galaxies form and how baryons modify halo structure. Such surveys are likely to tell us a great deal about the details of the galaxy formation process, perhaps of greater interest to astrophysicists than their original goals [33].

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